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QUADROTORS UNMANNED AERIAL VEHICLES: A REVIEW

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Abstract- Quadrotors are Vertical Take-Off and Landing aerial vehicles with many potential applications ranging from mapping to supporting rescue operations. This paper aims to provide an overview on various works carried out on the quadrotor, from the perspective of control and dynamic modelling. Also in this paper, based on the information summarized from 160 researches available, different control targets and flight missions are analysed and classified, and according to it, a general flight mission map is introduced. In addition, history of advances in development of quadrotors and set-ups proposed when performing experimental researches on quadrotors is presented.

Index terms: Quadrotor, review, history of advances, dynamic modelling, assumptions, control, flight missions, setup.

I. INTRODUCTION

Quadrotor is an unmanned aerial vehicle. Depending on the flying principle and propulsion mode, one can classify the aerial vehicles in multiple categories as shown in figure 1.

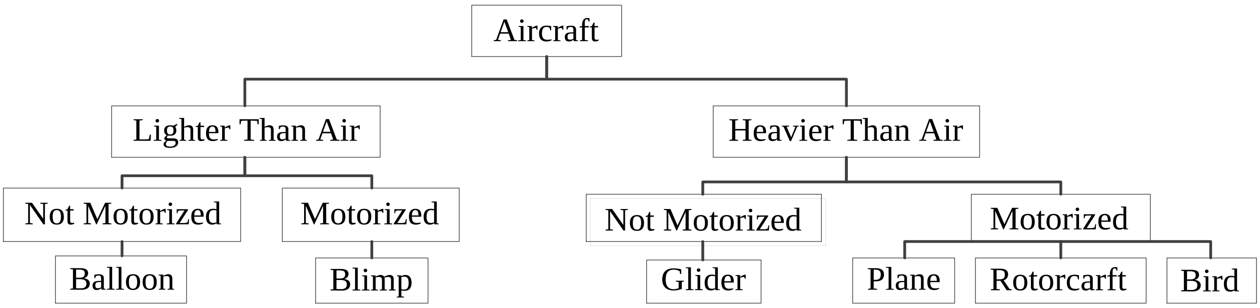


Figure 1. Aircraft classification depending on the flying principle and propulsion mode

In the motorized class, the bird-like Micro Aeral vehicle (MAV) can be considered as the perfect example of fast navigation. Vertical Take-Off and Landing (VTOL) and UAV are classified under the same category[1]. UAVs themeselves could be classified as follows:

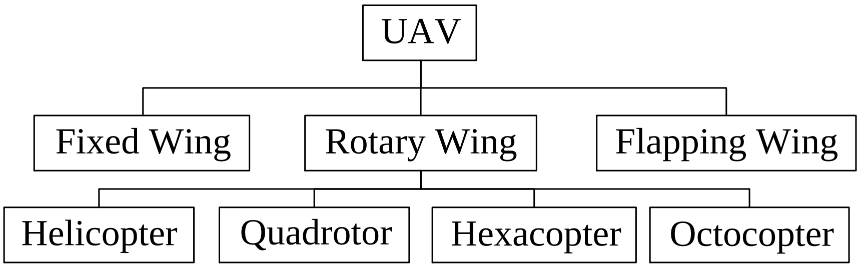


Figure 2. UAVs classification

In the civilian field, fixed-wing UAVs are most used for long-distance, long-range and high-altitude missions. Generally, they are useful in scientific applications such as meteorological reconnaissance and environmental monitoring. Due to its usage in the military field, it is equipped with similar systems in order to achieve its navigation tasks [2, 6].

Flapping-wing UAVs try to duplicate the way birds or insects fly. Most of them are still under development. Belonging to the class of micro UAVs, they have extremely low payload capability and low endurance. Among their interesting characteristics it can be mentioned that the flapping wing UAVs have low power consumption and can perform vertical take-off and landing [4-9].

Rotary wings UAVs, which are also called Vertical Take-off and Landing (VTOL) rotorcrafts, are normally used on missions that require hovering flight. Rotary wing aircrafts are also less susceptible to air turbulance compared with fixed wing aircrafts of similar dimensions [10]. The common example of rotary wing UAVs are helicopters which are a two-rotor aircraft with a main rotor giving the thrust and an anti-torque tail rotor. Another example of rotary wing aircrafts could be quadrotors. A comparison between flapping-wing, fixed wing and rotary wing are available in table 1. In this comparison charachteristics of rotary wings are scored based on the quadrotor type. [11-13]

Table 1: Comparison between rotary wings, fixed wings and flapping-wings
(High: ⊕, Medium: ⊖ , Low: ○)

	Rotary wing	Fixed wing	Flapping wing
Maneuver [14]	⊕	○	⊖
Cost [15]	⊖	○	⊕
Construction and Repairing [16-18]	⊖	○	⊕
Civilian Application [12, 15, 19, 20]	⊕	○	⊕
Military Application[11]	⊖	⊖	⊖
Energy Consumption[11, 12]	○	⊖	⊕
Flight safety [16, 17]	⊖	⊕	○
Range[11]	⊖	⊕	○

Due to some unique abilities of quadrotors such as high maneuverability, small size, and easy control, quadrotors have been widely used. Their most signficant applications are search-and-rescue and emergency response. They are also used in homeland security, military surveillance, and search and destroy. Miniaturization of quadrotors has enabled them to be used for border patrol and surveillance. Moreover, they have potential applications in other areas such as earth sciences where they can be used to study climate change, glacier dynamics and volcanic activity or for atmospheric sampling [21]. A detailed analysis of possible applications of quadrotors has been provided in[22]. For applications such as search and rescue, quadrotors were used as multi-agent systems [23-25].

II. MECHANISM OF FLYING

Quadrotors are small agile vehicles controlled by the rotational speed of the four rotors. The position of rotors arrangements relative to the body coordinate system cause two different types of quadrotor configurations: the “x” configuration and the “+” configuration shown in figure 3 and 4 [26, 27]. An x-configuration quadrotor is considered to be more stable in comparison to + configuration, which is a more acrobatic structure [21]. The four rotors are aligned such that the rotors on opposite ends rotate in the same direction and the other two in the opposite direction.

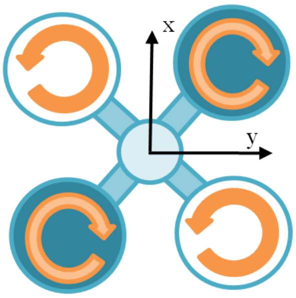


Figure 3. Cross Configuration

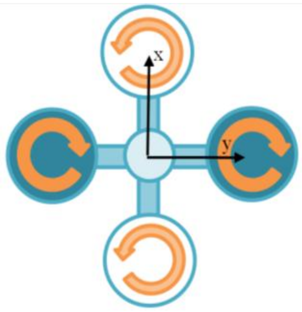
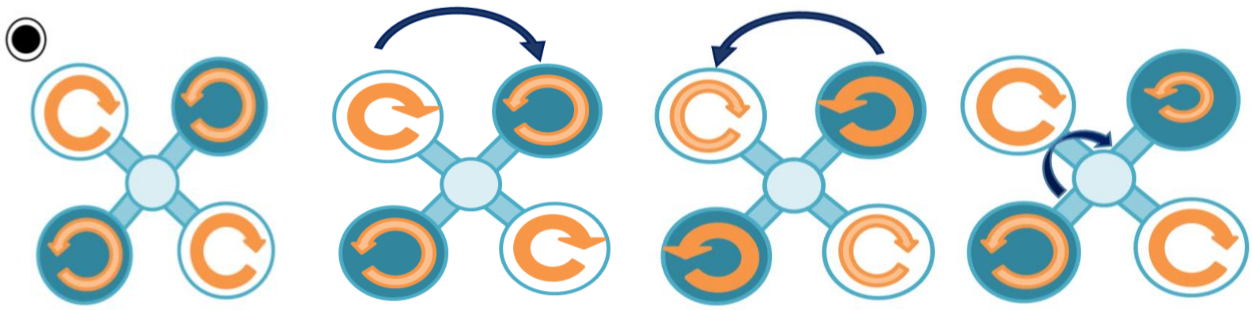


Figure 4. Plus Configuration

The quadrotor has six degrees of freedom, three translational and three rotational movements. As the number of system inputs is lower than the number of outputs, quadrotors are classified under under-actuated category. The flying mechanism of the vehicle is simple. The quadrotor rotates on three axes by simply adjusting the angular velocity of each rotor in relation to the other three. If half of the rotors rotate clockwise and the other half rotate counter clockwise at the same speed, the net yaw is zero (Fig. 5. a). A difference in speeds between the two pair motors creates a net yaw (Fig. 5. b and c). Different speeds in opposite motors create a net roll or pitch (Fig. 5. d) . Forward (backward) motion is maintained by increasing (decreasing) speed of the front (rear) rotor while decreasing the (increasing) rear (front) rotor speed simultaneously which means changing the pitch angle. Left and right motion is accomplished by changing roll angle in the same way.



(a) (b) (c) (d)

Figure 5. Quadrotor movement

III. OVERVIEW OF THE EARLY HISTORY OF QUADROTORS

In 1907 the Breguet Brothers built the first quadrotor. The flights of the Gyroplane No. 1 (figure 6) are considered to be the first manned flight of a helicopter, but not an untethered flight. Lack of stability and proper control mechanism caused the machine to never fly completely freely [28, 29]. After Gyroplane No. 1, other attempts were done on manned quadrotors such as Flying Octopus in 1922 by Georges de Bothezat (figure 7) and Oemichen No.2 (figure 8) by Etienne Oemichen in the same year, Convertawings Model A in 1922 by Oemichen and de Bothezat, the Curtiss X-19 (figure 9) in 1963 by Curtiss-Wright corporation, the Bell X-22A in 1966 by Bell Aircraft corporation and the fly vehicles of the Moller company [30].

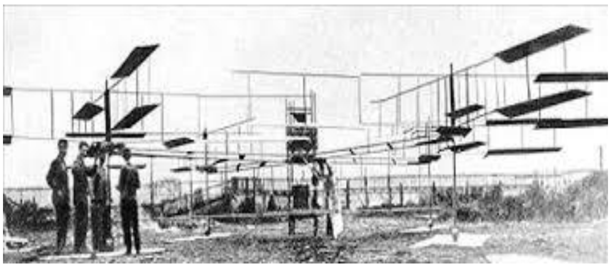


Figure 6. Bréguet Richet Gyroplane No. 1

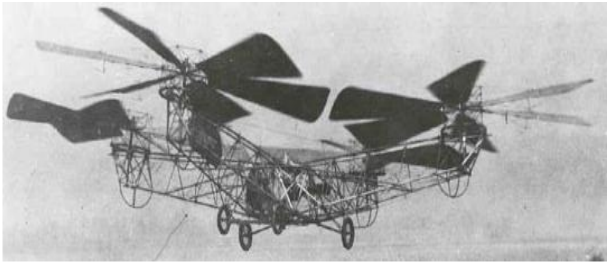


Figure 7. Georges de Bothezat

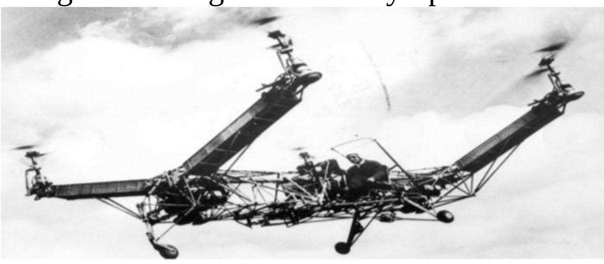


Figure 8. Oehmichen No.2

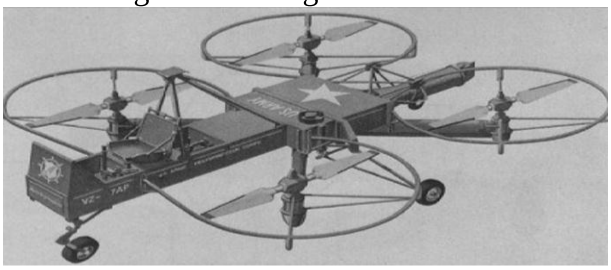
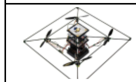


Figure 9. Curtiss-Wright

IV. RESEARCH PROJECTS ON QUADROTORS

After these attempts, improvements of the knowledge of control theory and technology allowed the development of unmanned quadrotors. After those imrovements, several research laboratories and universities started projects with quadrotors (Table 2). All in all, the development of full autonomous flight in all environment is still a challenge.

Table2. Research projects on quadrotors

	University/ Organization	Project	Year	Early studies	Recent studies
	Dragan flyer	V Ti [31]	1998	Commercial product	Commercial product
	Stanford	Mesicopter-I., Kroo [33]	2000-2012	-Feasibility and capability of the vehicle -Design and Manufacturing Techniques [33]	-Control of Multiple UAVs for Persistent Surveillance [32]
	ANU	P. Pounds's thesis [36]	2002-2014	-Dynamic modelling based on Newton-Euler Method -Control attempt [36]	-Triangular Quadrotor[34] - Output tracking for quadrotor-based aerial manipulators[35]
	FEIT, ANU	X-4 Flyer, P., Pounds [36]			
	Uni. Pennsylvania	E. Altug [39]	2002-2012	Yaw and height control using Visual feedback control techniques [39]	-Improving disturbance rejection and robustness of the vehicle using Fuzzy logic controller [37] -Obstacle avoidance using Catadioptric cameras [38]
	Uni. Compiègne	P. Castillo's thesis, A. Dzul [40]	2003- 015	-Dynamic modelling using Lagrange approach -Linear trajectory tracking [40]	Precise measurement and prediction of position and orientation of the vehicle in the presence of external perturbation (out- door control of the quadrotor) [40, 41] -Quaternion control scheme [42] -Velocity regulation of the quadrotor [43]
	Uni. Aalborg	X 3D [44]	2004	---	---
	Stanford	Starmac [46]	2004-2011	-Altitude and attitudes control in presence of wind [46]	-Collision avoidance and control of the vehicle in aggressive maneuver utilizing combination of hybrid decomposition and reachable set theory [45]
	Stanford	StarmacII [46]			
	EPFL	Bouabdallah & Siegwart [30]	2004-2011	-Autonomous control of the vehicle in indoor environment [30]	-Robust control of quadrotor in presence of model uncertainties and external disturbances [47]
	Cornell University	Eryk Brian Nice's thesis and R. D'Andrea, [49]	2004- 2015	-Nonlinear dynamic modelling and hover control [49]	-Iterative learning controller for improving the performance of the vehicle in highly dynamic open-loop maneuver [48]

	Middle East Technical University, Turkey	F.B. Çamlica's thesis, C Özgen [50]	2004-2014	Hover control [50]	-Trajectory tracking in presence of disturbance [49]
	Technology university of Malaysia	Weng and Shukri [51]	2006	---	---
	Uni. Oldenburg	M. Kemper's thesis [54]	2006-2009	Robust control of quadrotor respect to variable center of gravities [54]	Way point navigation and trajectory optimization [52, 53]
--	Cranfield university	I.D. Cowling and J.F. Whidborne	2007-2010	Optimal trajectory generation around obstacle [56]	-Trajectory generation and tracking in presence of gust and control of the vehicle in chimney mission [55]
	MIT	P. Tournier and J.P. How [59]	2007- 2015	Autonomous control of quadrotor by using visual servoing method [59]	-Maneuver learning from demonstration (communication with human) [57] -Control of variable-pitch quadrotor [58]
	Uni. TUDelft	Menno Wierema and Ir. C. de Wagter [60]	2007	Autonomous indoor navigation	----
	IARC Team -Virginia Tech. Uni.	IARC Team Quadrotor [61]	2009	Carrying payload	-----
	Univ. Maryland	AVL's Micro Quad (J. Sean Humbert) [63]	2009-2015	Robust visual navigation [63]	- robust stabilization and command tracking behavior in obstacle-laden environments [62]
	Azad University of Ghazvin	Farshid Jafari Harandi [64]	2010	Outdoor navigation	-----
	CrazyFlie	CrazyFlie [160]	2011	Commercial product	Commercial product
	Commercial product	Ascending Technologies Hummingbird [65]	-----	Commercial product	Commercial product
	Silverlit	X-UFO [66]	------	Commercial product	Commercial product
	microDrones GmbH	MD4-200® [67]	-----	Commercial product	Commercial product

Modelling a vehicle such as a quadrotor is not an easy task because of its complex structure. Different assumptions based on various missions are considered in quadrotors modelling. In what follows these assumptions are introduced.

(1). ***Gyroscopic effect*:** The gyroscopic moment is induced on the aircraft from both the rigid body and the four rotors. The gyroscopic effect of rotors is smaller than the one caused by the rigid body rotation. In [68] Bouabdallah and Siegwart considered both gyroscopic effects mentioned above. However, in many cases the gyroscopic effect of rotors has been neglected [69, 70].

(2). ***Ground effect:*** Quadrotors operating near the ground experience thrust augmentation due to better rotor efficiency. It is related to a reduction of the induced airflow velocity which is called the ground effect [71]. There are some approaches to deal with this effect. Guenard et al. [72] uses a function of height to increase the thrust coefficient. Reference [71] used a simple model to consider the variation of the induced inflow velocity. Cheesman [73] uses the image method to state the ground effect at constant power. In heights upper than a specific altitude, ground effect could be neglected [74].

(3). ***Drag and lift force of propeller rotation:*** As the blades of the propellers rotate in the air, a damping force and a lift force are generated. Thrust and drag force can be defined in terms of aerodynamic coefficients. Reference [74] demonstrates that these forces are polynominally dependent on the rotor speed. Aerodynamic coefficients have been discussed in [71]. At hover, it can be assumed that the thrust and drag are proportional to the square of the propellers' rotation speed [75, 76].

(4). ***Structure:*** Most of the works on quadrotors have assumed that the structure of the quadrotors is rigid and symmetrical, therefore the inertia tensor of the quadrotor must be diagonal [77].

(5). ***Propeller shaft:*** Propellers' axis of rotation is assumed perfectly aligned with the Z-axis [78].

(6). ***Friction force and moment:*** Friction force and moment which have been demonstrated in Reference [19] are the result of air friction on quadrotor's body in translational and rotational movements. Due to the low speed of translational and rotational movement of quadrotors, friction force and moment could be neglected [79, 80].

(7). ***Coincidence of center of mass (COM) and coordinate system origin (CSO):*** Most of the works on quadrotor have assumed that COM and the CSO are coincidental [81].

References [82, 83] presented a dynamic model with differences in the location of COM and CSO.

(8). ***Blade flapping:*** Blade flapping effect is very important, as the tilting rotor can introduce significant stability effects for the vehicle. Also it is critical to understanding oscillatory modes of the vehicle. Pounds [84] and Hoffmann [85]investigated the blade flapping in their researches.

(9). ***Critical conditions in taking-off and landing:*** Critical scenarios in taking off and landing, such as in the presence of sloped terrains and surrounding obstacles, have been investigated in reference [86].

(10). ***Wind:*** Wind has a significant nonlinear effect on the navigation, inertial orientation and rates of the vehicle. Modelling of wind in order to design a controller to track the path of the quadrotor in wind has been done in Reference [87].

V. QUADROTOR DYNAMIC MODELLING

The dynamic model of a quadrotor describes the attitude and position of the system and consists of mathematical equations that are comprised of all the forces that can act on the system at a given time. Based on input controls, two types of dynamic models have been used to simulate the behaviour of a quadrotor and control of the system. Type one is among those models that use motors' speed as input controls and do not consider the model of the motor while type two is among those models that consist of the dynamic model of motor and use motors' voltages as input controls. In general, full mathematical modelling of a quadrotor can be divided into two categories: body modelling and propulsion system modelling, which includes propeller modelling and engine modelling. The following paragraphs reveal different attempts that have been made to model these parts.

a. Body modelling

Different approaches have been used to model body dynamics of quadrotors. Reference [88] presented a Lagrangian dynamic model of quadrotors. In [89] Newton–Euler approach and in [90] a quaternion formation of dynamic equations are used to achieve a body dynamic model. Also the superposition method and the system identification are used in dynamic modelling of quadrotors' body in references [71] and [91, 92] respectively. And to combat unknown dynamic reference [70] used the neural network. In [166] dynamic of the quadrotor at the presence of a sliding mass is discussed. In this study, a method named DAS (Differential Algebric Splitter) is used to simulate the nonlinear dynamics of the vehicle [167].

b. Motor modelling

Reference [93] presented a nonlinear dynamic model for quadrotors including both dynamic model of body and propulsion system. Reference [82] presented a complete dynamic model of motor which included mechanical parts (gear and various frictions) and electrical parts. In this research, motor is connected through a gear to reduce the speed. In reference [94] the identification method is used to predict the model of a motor. Another identification method based on the neural network is presented in [95] to model the motor. In all researches mentioned above, propulsion system uses a brushless DC motor. Modelling of a brush DC motor for quadrotor is discussed in reference [60].

c. Propeller modelling

Modelling of propeller consists of aerodynamic equations that models lift and drag forces and moments based on the rotor speed and aerodynamic coefficients. References [96-98] discussed the identification of aerodynamic coefficients and driving aerodynamic equations of blade. Compared to an ordinary propeller, a ducted fan propeller is more efficient. In reference [99] a detailed comparison between a quadrotor with ducted fan propeller and one with ordinary propeller has been provided. Modelling of ducted fan propeller has been presented in reference [100].

d. Case studies on modelling

In addition to previously mentioned researches which have been done on modelling of quadrotors, there are some other researches focusing on quadrotor modelling for specific tasks. Reference [101] modeled a quadrotor with suspended load. Also, modelling a quadrotor with tilt wing mechanism was presented in [102].

VI. FLIGHT MISSIONS AND CONTROL

As quadrotors have been widely used in the last few decades, researchers have portrayed considerable amount of determination to control these flying vehicles. Choosing the control technique depends on control target the vehicle must meet. Figure 3 illustrates the hypothetical mission profile for the quadrotor consisting all flight phases which might be chosen as a control goal for quadrotor.

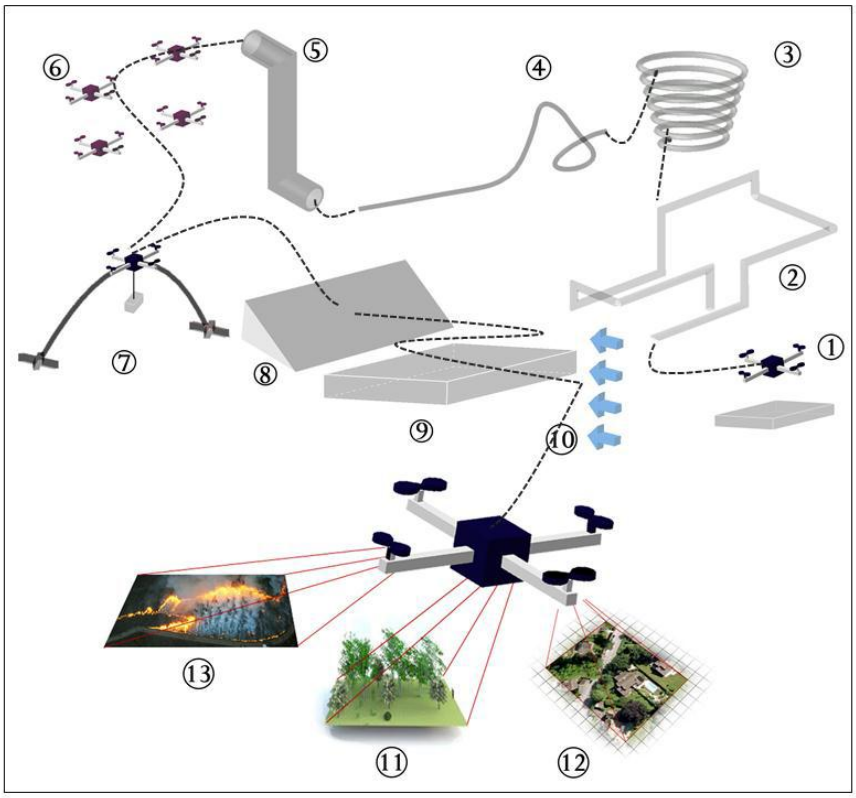


Figure 10. Hypothetical mission profile

In the next paragraphs, each flight mission will be described and control researches in each phase will be reviewed.

Phase 1- Stabilization at hover condition: On this mission, quadrotor must be stabilized at hover condition. Accurate control of attitudes is the required control ability quadrotor must have. References [84, 103-106] control quadrotor on this mission.

Phase 2- Straight line trajectory: The mission demonstrates that the quadrotor is able to smoothly track straight line trajectories rather than being kept stabilized at hover condition [107-117].

Phase 3- Circular trajectory: Circular trajectory is a mission to prove that the quadrotor is able to freely maneuver not only in a straight line. In this mission, the vehicle revolves around a given point in X-Y plane with constant or variable radius and simultaneously increases or decreases its height [39, 68, 74, 81, 96, 102, 118-127].

Phase 4- Complex maneuver: A complex flight manoeuvre can be defined by specifying a concatenation of flight modes together with conditions for switching between them. This type of aerobatic manoeuvre involves large angle transitions between flight modes. These rapidly changing directions are mostly carried out at fairly high speeds (roughly 8 m/s). References [90, 97, 127-130] have done researches on control of quadrotor in this type of manoeuvre.

Phase 5- Passing chimney: The wall effect on the aerodynamics of propulsion system is similar to the ground effects. Passing chimney is a mission in which quadrotor is fully surrounded by walls. Depending on the distance from the wall, dynamic of quadrotor varies due to the changes in aerodynamic coefficient. Being able to adapt to different dynamics and having enough accuracy in trajectory tracking are the most important parameters that must be met in control of the vehicle on this mission [20, 55, 131].

Phase 6- Collision avoidance: In autonomous flights, in order to ensure the safety of the quadrotor, the vehicle must be able to perform obstacle avoidance. In addition, there are other important tasks that this mission includes: multi-vehicle collision avoidance, collision-free trajectory generation, and obstacle avoidance in tight areas. References [46, 59, 132-137] examined this issue.

Phase 7- Picking up, loading and releasing object: On this mission, quadrotor can carry and take away a payload and release it in a specific zone. As the vehicle can take different payloads on its different flight missions, unknown mass is one of the main uncertainty parameters associated with the quadoror UAV's dynamic model. Dynamics of the quadrotor significantly alter by the addition of payloads. As it will be unpractical to measure the mass value of the vehicle together with its payload during each flight, it is necessary that the robots be able to estimate the inertia of the payload and adapt to it in order to improve tracking performance. Payload transport could be done by the use of a single quadrotor or multiple vehicles. There are many challenges in aerial grasping for micro UAVs. The biggest challenge arises from their limited payload, while multiple robots can carry larger payloads. Quadrotor can carry payloads with grippers or with cables. Payload transport with cable or flying with a suspended load is widely used for different kinds of cargo transport. Flying with a suspended load can be a very challenging and sometimes hazardous task because the suspended load significantly alters the flight characteristics of the quadrotor. Control of quadrotor on this flight mission was investigated in references [83, 101, 138-142].

Phase 8- Take-off and landing in hard condition: On this mission, the quadrotor is expected to land and perch at carefully selected position. The position might be sloped terrain, horizontal or flat pads. References [86, 87, 143] investigated the control of quadrotor in such conditions.

Phase 9- Operating near ground, take-off and landing: In take-off control mission, the quadrotor is commanded to smoothly take-off and ultimately hover at a desired height. And as opposed to take-off, in landing mission the vehicle descends from initial height to 0m.

Quadrotor operating near ground experiences a "ground effect" that makes the control of quadrotor more difficult compared to a flight at a long distance from the ground. References [23, 71, 85, 144, 145] worked on control of quadrotor on such missions. Control of quadrotor on take-off and landing mission is complicated, because the ground effect near the ground must be considered too. Furthermore, in this flight regime, the aerodynamic coefficients of propulsion system could not be assumed constant.

Phase 10- Disturbances: Besides the control targets mentioned above, being designed for indoor or outdoor environment conditions has a strong effect on choosing the control techniques. Control of the vehicle in presence of disturbances such as wind and gust in outdoor flight condition is an issue that many researches focused on [145-148].

Complex missions

Recent applications of quadrotor include combination of the mentioned missions in order to do more complex tasks such as pipe-line surveying, border patrolling, exploration, cartography, disaster relief operation, so on. Such kinds of missions can be categorized in three different classes of missions as follows.

Phase 11- Patrolling: In monitoring a known environment, like plant inspection and border patrolling, quadrotor must meet combination of aforementioned missions such as obstacle avoidance, take-off and landing, navigation in presence of different kinds of disturbances for outdoor patrolling and trajectory tracking. References [149-151] discuss control of the vehicle on such kinds of missions.

Phase 12- Simultaneous localization and mapping (SLAM): SLAM is a mission in which quadrotor build maps, while at the same time estimating precisely its location within an unknown environment. The mission is significantly useful in many applications including search and rescue, exploration, cartography, military applications and environmental monitoring. In terms of requirements, image analysis is a basic requirement to conduct the mission. In addition, since weight and power consumption are significantly important to carry out the mission in a longer period of time, sensor and equipment selection are considered as challenging issues. References [110, 152-154] address the control of the vehicle at this flight phase.

Phase 13- Navigation in reduced visibility conditions: There are many applications in which the vehicle needs to conduct a mission within an environment with reduced visibility like an environment with smoke or dust particles. In such kinds of conditions, being highly disturbed by noise induced in measurement process by particles of smoke or dust, the regular sensors which are used in SLAM mission within normal condition, like laser range finders and cameras, cannot be used. Different SLAM algorithm and techniques are introduced to deal with navigating the vehicle within this condition. References [155-159] have done researches on control of the quadrotor in this mission.

VII. TEST BED

The development of a control system for flying robots requires the development of an adequate test-bench for the preliminary experiments. In recent years, many set-ups have been designed and built to provide required condition for conducting experimental tests on quadrotor and for evaluating the performance of the vehicle. Set-ups and experiments can be divided into four categories:

1) Aerodynamics
2) Attitude and altitude control
3) Six-degrees of freedom motion control
4) Identification of the vehicle parameters

Experiments and developed set-ups will be reviewed at this subsection.

a. Aerodynamics

Reference [98] conducted some experiments on quadrotor to examine the thrust variation with respect to the distance from the ground and the wall. Also an experimental set-up for thrust measurement was designed and built. In [88] different rotor blades were tested for maximum thrust production versus power input. In [85] thrust test stand was designed to measure thrust, side force, and torque using a load cell. In order to determine the minimum required space between the motors, a test set-up in reference [61] was designed and developed.

b. Attitude and altitude control

In [160] Scott D. Hanford attached the quadrotor to a Whitman training stand. The training stand allows the quadrotor to rotate on its yaw, pitch, and roll axes and move vertically. In reference [77] a set-up was built to measure the attitude angles and angular velocities. In [161] a test-bench which allows the quadrotor only the three rotations (roll, pitch and yaw) was presented. In [77, 161] a set-up was presented in order to control the roll and pitch angles. A single degree of freedom test stand was built in [61] to examine the performance of roll and pitch control algorithms on quadrotor. Also, in this reference a yaw stand was constructed. In [61] a test has been designed to control attitudes in hover mode.

b.i Six-degrees of freedom motion control

In [162, 163] a set-up is built to provide six degrees of freedom motion for the vehicle.

b.ii Identification of the vehicle parameters

In [164]**,** in order to find a linear experimental relationship between the motor voltage and propeller thrusts, a test set-up was designed and built. In [77] a test bed was designed to identify the model of propulsion system. In [61] thrust testing was performed to characterize different combinations of motors and propellers as variable options for the vehicle. In [164] a test apparatus for rotor performance testing was designed.

VIII. CONCLUSIONS

In this paper different projects focusing on quadrotor were presented and different assumptions and researches about dynamic modelling of quadrotor were reviewed. Dynamic modelling of the body of the vehicle, the propeller, and the rotor were discussed separately. In addition, different methods which are used in dynamic modelling of quadrotor were introduced and control targets of quadrotor were discussed. Furthermore, a mission profile including all control targets was presented, and based on the mission profile researches with control target were classified. Finally, experimental set-ups which are developed to evaluate the performance of quadrotor were reviewed.

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